ABSTRACT

The Cenozoic rocks of western Owyhee County, Idaho, are principally lavas and welded tuffs that range in age from Eocene to Pleistocene. The Eocene lavas and tuffs are intermediate in composition, as much as 1,000 meters thick, and restricted to a small area in the eastern part of the Owyhee Mountains. Volcanic rocks of Oligocene age are also restricted areally and form a local accumulation as much as 1,160 meters thick in the northern Owyhee Mountains. The Oligocene rocks are lavas that contain olivine or pyroxene phenocrysts or both. The Oligocene and Eocene volcanic rocks and the Cretaceous granitic rocks form the eroded basement surface upon which widespread olivine basalts and dark gray latite and quartz latite lavas of Miocene age were deposited. These younger rocks of basalt to latite composition are at least 1,000 meters thick. They are overlain by thick, widespread rhyolite tuffs and lavas that are the principal subject of this paper. The rhyolites, in turn, are overlain by basalt lavas that are 8-10 million years old on the Owyhee Plateau but as young as Pleistocene on the Snake River Plain.

The rhyolitic rocks were erupted from vents in and adjacent to the Owyhee Mountains and Owyhee Plateau from 16 to about 10 million years ago. They are mainly welded tuffs that, regardless of their source, have one feature in common: namely, internal characteristics indicating en masse viscous lavalike flowage. On the basis of the tabular nature of the rhyolitic deposits, their broad areal extent, and the local preservation of pyroclastic textures at the bases, tops, and distal ends of some of the deposits, we have concluded that the rocks were emplaced as ash flows at extremely high temperatures and that they coalesced to liquids before final emplacement and cooling.

The rhyolites generally are crystal poor. Those that were erupted from the Silver City Range about 16 million years ago commonly contain fewer than 3 percent phenocrysts consisting of quartz, plagioclase, and alkali feldspar; most of these rocks contain sparse flakes of biotite and are the only rhyolites in the study area that do. Rocks that are 14 million years to about 10 million years old contain only pyroxenes, chiefy ferriferous and intermediate pigeonites, as mafic constituents. Rhyolites erupted from the Owyhee Plateau include two sequences that were mapped over areas having diameters of about 100 kilometers. These two sheets are the 13.8-million-year-old tuff of Swisher Mountain, which was erupted from the Juniper Mountain volcanic center, and the 10-million-year-old tuff of Little Jacks Creek which is inferred to have been erupted from a source on the part of the Owyhee Plateau that lies just east of the study area. The two inferred source areas are expressed as gentle domes without structural features indicative of cauldron subsidence.

Iron-titanium oxide determinations reveal that both the tuff of Swisher Mountain and the tuff of Little Jacks Creek were erupted at a minimum temperature of 1090°C. We conclude that both tuffs formed in water-deficient levels of the crust, probably at depths as great as 15-25 kilometers, and that the tuffs were erupted from these great depths.

INTRODUCTION

Owyhee County, Idaho, west of 116° longitude (Figure 1), was mapped at a scale of 1:125,000 during the summers of 1977 and 1978 (Ekren and others, in press, 1981) as part of the U. S. Geological Survey’s investigation of potential geothermal areas. The present report briefly summarizes the results of this investigation. The reader interested in more detailed descriptions of the rocks or more complete discussion of rock chemistry and petrogenesis should consult the references noted above. The mapping and associated stratigraphic studies focussed on the voluminous rhyolitic rocks exposed in the Silver City Range (Owyhee Mountains) and the Owyhee Plateau of extreme southwestern Idaho because these strata underlie the principal recharge area and are the
Figure 1. Generalized geologic map of western Owyhee County, Idaho (modified from Ekren and others, 1981).
DESCRIPTION OF MAP UNITS

Qa, alluvium and eolian deposits
QTa, older alluvium
QTu, alluvium and eolian deposits undivided
Tb, Bonaby Basalt
Tij, tuff of Little Jacks Creek
Tbc, tuff of Browns Creek
Twc, tuff of Wilson Creek
Tjs, Jump Creek Rhyolite of Kileman and others, 1965
Tjsb, tuff of The Badlands
Tjv, tuff of upper lobes
Tjx, tuff of lower lobes
Ts, tuff of Swisher Mountain
Tsa, Sucker Creek Formation of Kileman and others, 1965
Tas, arkose sediments
Tbn, rhyolite of Black Mountain
Tsn, sediments of Reynolds
Tsc, rhyolite of Silver City
Tr, intrusions
Tl, latite
Tlb, basalt
Tob, andesite and basalt
Td, dikes
Tcv, Challis Volcanics
Kg, granitic rocks
Kgh, hornblende gabbro
pKm, metamorphic rocks

CORRELATION OF MAP UNITS

Figure 1. continued.
principal thermal reservoir rocks of the Bruneau-
Grand View geothermal area (Young and Whitehead,
1975).

STRATIGRAPHY OF ROCKS
OTHER THAN RHYOLITE

The northern mountainous part of Owyhee County,
variously called the Owyhee Mountains or the Silver
City Range, is underlain by Cretaceous granitic rocks
and by a variety of Tertiary volcanic rocks from
Eocene to Miocene in age. The granitic rocks are
chiefly granodiorite and quartz monzonite, but they
include large masses of granite and porphyritic diorite
or granodiorite. Near South Mountain (Figure 1), the
granitic rocks are bordered by Cretaceous hornblende
gabbro and are roofed by pre-Cretaceous metasedi-
timentary rocks (Sorenson, 1927; Bennett, 1976). We
concur with Taubeneck (1971) and earlier researchers
(for example, Lindgren, 1900) that the granitic rocks
are an integral part of the Idaho batholith.

Rhyodacite and quartz latite lava flows and ash-
flow tuffs of Eocene age that correlate with the
Challis Volcanics (Axelrod, 1968) are locally exposed
38 kilometers east of South Mountain and are 500-
1,000 meters thick. One of these ash-flow tuff units
yielded a potassium-argon age of 44.7 ± 0.8 million
years (Armstrong and others, 1980).

Rocks of Oligocene age consist of a local accumu-
alation of olivine basalt and andesite lavas as much as
1,160 meters thick that are chemically dissimilar to
the overlying Miocene volcanic rocks (Table 1). The
Oligocene rocks contain olivine or pyroxene pheno-
crys or both, and a whole-rock analysis yielded a
potassium-argon age of 30.6 million years.

The Oligocene rocks and the Cretaceous granitic
rocks are unconformably overlain by widespread
Miocene volcanic rocks at least 1,000 meters thick.
These consist of interbedded olivine basalt and dark
gray latite and quartz latite (Table I). A basalt from
this sequence collected by Pansze (1975) yielded a
whole-rock potassium-argon age of 17 million years.
The basalt-latite sequence is overlain and intruded by
rhyolitic rocks, the major subject of this paper.

The rhyolitic rocks, in turn, are overlain in many
places on the Owyhee Plateau by widespread olivine
basalts and interbedded sedimentary rocks that cor-
relate with the Banbury Basalt of Malde and others
(1963). The sequence locally exceeds 300 meters in
thickness, and potassium-argon dates from nearby
exposures to the east and south range from about 8 to
10.5 million years (Armstrong and others, 1975). The
sedimentary rocks interbedded with the basalts include
a large variety of conglomeratic tuffaceous sandstones
and conglomerates containing well-rounded pebbles
and cobbles of dark gray chert and brown quartzite,
both of which were apparently derived from sources
in northern Nevada west of the Jarbidge Mountains.
Local accumulations of flat-bedded lacustrine silt-
stone and diatomite indicate intermittent ponding of
drainages during the basalt eruptions.

| Table 1. Chemical analyses and CIPW norms for some pre-rhyolite
| mafic and intermediate volcanic rocks, western Owyhee County,
| Idaho (modified from Table 1 of Ekren and others, in press). |
|  | Chemical Analyses |  | \( \text{SiO}_2 \) | 48.30 | 56.60 | 47.60 | 54.69 | 66.31 |
|  | \( \text{Al}_2\text{O}_3 \) | 15.94 | 17.28 | 15.58 | 15.15 | 13.60 |
|  | \( \text{Fe}_2\text{O}_3 \) | 3.33 | 4.03 | 3.23 | 1.92 | 1.63 |
|  | \( \text{FeO} \) | 6.67 | 2.22 | 8.25 | 7.75 | 3.38 |
|  | \( \text{MgO} \) | 7.47 | 3.97 | 8.04 | 4.81 | 1.85 |
|  | \( \text{CaO} \) | 8.42 | 6.48 | 8.89 | 7.30 | 3.27 |
|  | \( \text{Na}_2\text{O} \) | 3.48 | 4.27 | 2.75 | 2.90 | 2.69 |
|  | \( \text{K}_2\text{O} \) | 1.13 | 1.80 | 0.43 | 1.68 | 4.05 |
|  | \( \text{H}_{2}\text{O}^+ \) | 1.30 | 0.71 | 0.73 | 1.17 | 1.77 |
|  | \( \text{H}_{2}\text{O} \) | 0.79 | 1.00 | 0.71 | 0.60 | 0.57 |
|  | \( \text{TiO}_2 \) | 2.05 | 0.96 | 1.87 | 1.77 | 0.65 |
|  | \( \text{P}_{2}\text{O}_5 \) | 0.71 | 0.42 | 0.27 | 0.34 | 0.12 |
|  | \( \text{MnO} \) | 0.18 | 0.10 | 0.18 | 0.16 | 0.00 |
|  | \( \text{CO}_2 \) | 0.22 | 0.04 | 0.12 | 0.04 | 0.03 |
| | Sum | 99.96 | 99.88 | 99.65 | 100.28 | 99.92 |

| CIPW Norms |
| 0.00 | 7.91 | 0.00 | 7.44 | 25.17 |
| 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 6.82 | 10.83 | 2.59 | 10.08 | 24.52 |
| 30.08 | 36.80 | 23.69 | 24.91 | 23.33 |
| 25.06 | 23.08 | 29.42 | 23.71 | 13.40 |
| 4.78 | 2.76 | 7.50 | 4.40 | 0.93 |
| 3.27 | 2.38 | 4.73 | 2.32 | 0.49 |
| 1.12 | 0.00 | 2.30 | 1.94 | 0.41 |
| 6.72 | 7.69 | 8.83 | 9.83 | 4.23 |
| 2.31 | 0.00 | 4.29 | 8.23 | 3.47 |
| 6.31 | 0.00 | 4.78 | 0.00 | 0.00 |
| 2.39 | 0.00 | 2.56 | 0.00 | 0.00 |
| 4.93 | 4.79 | 4.77 | 2.83 | 2.42 |
| 0.00 | 0.80 | 0.00 | 0.00 | 0.00 |
| 9.88 | 1.86 | 3.67 | 4.41 | 1.27 |
| 1.72 | 1.01 | 0.65 | 0.82 | 0.29 |
| 0.51 | 0.09 | 0.28 | 0.09 | 0.07 |

1. Oligocene K-rich olivine basalt.
2. Oligocene andesite; average of 3 analyses.
3. Miocene basalt; average of 2 analyses.
4. Miocene basaltic andesite; average of 2 analyses.
5. Miocene quartz latite; average of 2 analyses.
Lacustrine sedimentary rocks and intercalated basalt units of Pleistocene age on the Snake River Plain at the northern boundary of Owyhee County were not examined in detail during this study, but are currently being mapped by H. E. Malde of the U. S. Geological Survey (written communication, 1980).

**STRATIGRAPHY OF PRINCIPAL RHOLITE UNITS**

**HISTORICAL REVIEW**

The rhyolite of the Owyhee Mountains and Plateau has puzzled geologists for many years. The main problem has been whether the bulk of the rocks are flow-layered welded tuffs or rhyolite lava flows. Lindgren (1900) did not concern himself with this problem because the concept of ash flow had not as yet been developed. Later geologists found themselves in a predicament in correctly identifying the rocks, because in most places the rocks displayed features indicative of lava flows, but in other places they showed some textures suggestive of welded tuffs as described by Smith (1960). The later geologists included Littleton and Crosthwaite (1957), Asher (1968), McIntyre (1972), Pansze (1975), Bennett and Galbraith (1975), Neill (1975), and Bennett (1976). Most, but not all, of these authors concluded that the rocks must be welded tuffs, primarily on the basis of their widespread areal extents.

We infer that most of the rhyolite units in the Owyhee area were emplaced as ash flows that coalesced to liquids before final emplacement and cooling on the basis of the following features: (1) the broad areal extent and tabular nature of the flows; (2) local presence of pumice and shards at the base, top, and sides of some of the units, and also within the interiors of some cooling units; (3) ubiquitous internal flowage features indicative of liquid flow; (4) the presence of flow breccia locally at the base of nearly every unit; and (5) the presence of flow-aligned incipient microlites in glassy zones which shows that liquefaction in these zones was complete.

**RHYOLITE UNITS OF SILVER CITY RANGE AND ADJACENT AREAS**

Flow-layered rhyolites, which for the most part contain only a small percentage of small phenocrysts (Figure 2), form the backbone of the Silver City Range and large parts of the downdropped eastern and western flanks of the range. These rocks are the principal hosts for the silver-gold veins of the Silver City district. Isotopic data (Table 2; Armstrong, 1975; Pansze, 1975; Dalrymple, written communication, 1977) show that the rocks are about 16 million years old and that the associated silver-gold mineralization is about 16-15.2 million years old (Armstrong and others, 1980).

Field relations show that some of the Silver City
Table 2. Potassium-argon ages for volcanic rock units from western Owyhee County referred to in this report. [For more complete data see Ekren and others (in press). Sources of data: (A) Armstrong and others (1980); (B) Armstrong (1975), recalculated using currently accepted constants (see Steiger and Jager, 1977); (C) Ekren and others (in press).]

<table>
<thead>
<tr>
<th>Unit</th>
<th>K-Ar age (m.y.)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jump Creek Rhyolite</td>
<td>11.1 ± 0.2</td>
<td>A</td>
</tr>
<tr>
<td>Tuff of Browns Creek</td>
<td>11.2 ± 0.65</td>
<td>A</td>
</tr>
<tr>
<td>(average of 2 analyses)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tuff of The Badlands</td>
<td>12.0 ± 0.2</td>
<td>A</td>
</tr>
<tr>
<td>Tuff of upper lobes</td>
<td>13.9 ± 0.5</td>
<td>C</td>
</tr>
<tr>
<td>Tuff of lower lobes</td>
<td>13.8 ± 0.5</td>
<td>C</td>
</tr>
<tr>
<td>Tuff of Swisher Mountain</td>
<td>13.5 ± 0.2</td>
<td>A</td>
</tr>
<tr>
<td>Do.</td>
<td>14.2 ± 0.4</td>
<td>A</td>
</tr>
<tr>
<td>Rhyolite of Black Mountain</td>
<td>15.7 ± 0.5</td>
<td>C</td>
</tr>
<tr>
<td>Rhyolite of Silver City Range</td>
<td>16.1 ± 0.3</td>
<td>B, C</td>
</tr>
<tr>
<td>(average of 6 analyses)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Andesite (Figure 1, Tab)</td>
<td>30.6 ± 1.0</td>
<td>C</td>
</tr>
<tr>
<td>Challis Volcanics (22 miles</td>
<td>44.7 ± 0.8</td>
<td>A</td>
</tr>
<tr>
<td>southwest of Grand View)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The rhyolite units grade laterally from near-source rocks, flow layered from base to top, to classic densely welded tuffs within a distance of a few kilometers. Most units were probably erupted from vents in and adjacent to the present Silver City Range, which is characterized by numerous feeder dikes, plugs, and extrusive domes of rhyolite (Panszé, 1975; Piper and Laney, 1926; Bennett and Galbraith, 1975). Many of the dikes were intruded after extensive north-to-southwest-trending normal faulting, especially in the De Lamar area, had occurred, thereby dating the start of normal faulting of that trend before 16 million years.

Rhyolite Units of the Western Flank

Numerous rhyolite masses on the western flank of the Silver City Range that were mapped and described by us (Ekren and others, 1981, in press) are too restricted areally to warrant description in this short review. However, two fairly widespread units in and adjacent to the open-pit mine at De Lamar are typical of the rhyolite units of the western flank. These units are the tuff of Flint Creek, which rests directly on basalt and latite lava flows of Miocene age, and the next overlying rhyolite, which we term the rhyolite of the millsite. Both of these units are included with the rhyolite of the Silver City Range on the accompanying geologic map (Figure 1).

Tuff of Flint Creek. Two genetically related ash-flow tuff cooling units, each from 30 meters to as much as 90 meters thick (Figure 2), are exposed in the canyon of Flint Creek (Figure 1) in the central part of T. 6 S., R. 4 W. Both units at Flint Creek grade upward from partially welded gray tuff at the base into flow-layered, purplish gray or reddish brown tuff at the top, in which pumice clasts are so flattened and stretched that they resemble laminations in rhyolite lava. In outcrops to the north near De Lamar, closer to the presumed source, all vitroclastic textures have been destroyed. There the rock is conspicuously flow layered from base to top and tends to weather to thin plates; it is gray, hydrothermally altered, and not easily distinguished from underlying gray crystal-poor latite lava flows. Distinction was made on the presence of sparse, fine (mostly 1 millimeter) grains of quartz in the rhyolite and on the lack of quartz in the latite.

The lower unit of the tuff of Flint Creek (Table 3) is principally a plagioclase-pyroxene tuff that contains a little quartz and little or no alkali feldspar and only trace amounts of biotite. It probably contains less SiO₂ and alkali metals than the upper unit, which has considerably more alkali feldspar and quartz phenocrysts (Figure 2).

Rhyolite of the millsite. Flow-layered rhyolite, overlying the tuff of Flint Creek but locally resting directly on the basalt and latite sequence, is relatively rich in phenocrysts compared with other rhyolite units of the Silver City-De Lamar area; it is exposed mainly near the millsite of the De Lamar open-pit mine. Flow layering in the rock in the vicinity of the millsite, as seen on aerial photographs, defines a broad whorl that is about 1.6 kilometers in diameter. This whorl possibly marks the vent of the rhyolite. Exclusive of the whorl, the rhyolite is at least 50 meters thick.

The rhyolite of the millsite, like the tuff of Flint Creek, contains little or no alkali feldspar in its basal part but grades upward to rock that is rich with phenocrysts of alkali feldspar (Figure 2) as large as 4 millimeters. The rock is pinkish gray and white and characterized from base to top by abundant vug-filling vapor-phase crystals. In places, large (about 15 centimeters) spherulites are present in the rock and conspicuously abundant on weathered slopes.

In exposures just south of the Flint Creek Mining District, the unit is separated from the underlying upper cooling unit of the tuff of Flint Creek by a zone of nonwelded, soft, yellowish gray tuff several meters thick. The soft tuff is overlain by aphyric flow-layered rhyolite that is highly altered. We inferred that this rock without phenocrysts is the rhyolite of the millsite. No pumice was noted in the flow-layered rhyolite in the Flint Creek area or in any other outcrop as far north as the northernmost exposures about 6.4 kilometers northwest of De Lamar and...
Jordan Creek. The distribution of the rhyolite, therefore, is known with reasonable certainty to extend from about 6.4 kilometers northwest of Jordan Creek on the north to Flint Creek on the south, a distance of about 21 kilometers. Although no conclusive evidence was found during the course of this study to show that the rhyolite of the millsite is a welded tuff, its distribution suggests that it may be.

Table 3. Chemical analyses and CIPW norms for rhyolitic rocks, western Owyhee County, Idaho. [Modified from Tables 4, 5, and 8, of Ekren and others, in press.]

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<td>0.06</td>
<td>0.07</td>
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</table>

### CIPW Norms

1. Tuff of Flint Creek, lower unit.
2. Rhyolite of the Silver City Range; average of 3 analyses.
4. Tuff of Mill Creek.
5. Tuff of Swisher Mountain; average of 2 analyses.
6. Tuff of lower lobes; average of 3 analyses.
7. Tuff of upper lobes; average of 2 analyses.
8. Rhyolite of The Badlands; average of 2 analyses.
10. Tuff of Wilson Creek.
11. Tuff of Browns Creek; average of 2 analyses.
12. Tuff of Little Jacks Creek; average of 7 analyses.
Rhyolite of the Central Silver City Range

Flow-layered and hydrothermally altered white and light gray rhyolite caps both the Silver City Range on Florida Mountain and a broad area south of War Eagle Mountain (Figure 1). In places, this capping rhyolite is at least 300 meters thick. Most of the exposed rock contains only 1-2 percent phenocrysts (Figure 2) that rarely exceed 1 millimeter in length. Three locally preserved vitrophyre layers at the base, middle, and top of the rhyolite section indicate breaks or partial breaks in cooling but show no mineralogic breaks. The vitrophyres differ modally from cooling units of the tuff of Flint Creek (see histograms, Figure 2) exposed along the western flank of the range, and their fewer and smaller phenocrysts preclude correlation with the rhyolite of the millsite. The three vitrophyres appear to be representative of most of the rhyolite section in the central Silver City Range, as we observed no rocks in our reconnaissance that were obviously different. No samples were collected from the mostly highly altered rhyolite on Florida Mountain which, according to Panzę (1975, p. 30), includes welded tuff breccias.

Rhyolite of the Eastern Flank

Phenocryst-poor, extensively flow-layered rhyolite crops out along the eastern flank of the Silver City Range from the south line of T. 6 S. to the north line of T. 4 S. (Figure 1). This sequence, which is at least 250 meters thick, was not sampled in its entirety, but several thin sections, mostly from exposures along creek beds, strongly suggest that most of the rocks are the same as those that cap the central Silver City Range. In contrast to the latter, the rocks along the eastern flank are mostly fresh and pale red, brownish gray, or reddish gray. Apache tears from the basal rhyolite in T. 6 S., R. 2 W. (Figure 1), yielded a potassium-argon age of 16.0 ± 0.3 million years (Table 2; G. B. Dalrymple, written communication, 1979). This age indicates the rocks along the eastern flank to be coeval with those on the western flank and at Silver City (Table 2; Panzę, 1975; Armstrong and others, 1980).

Several outcrops were found that confirm an ash-flow tuff origin for some of the eastern flank rhyolite units. One of these outcrops is along the Sinker Creek-Silver City road in NW 1/4, T. 4 S., R. 2 W., where the lowest rhyolite unit in the section rests directly on granite and the contact locally is nearly vertical. The foliation is defined by well-flattened pumice fragments in the basal vitrophyre, and thin sections show that these fragments are enclosed in a matrix of shards. The devitrified rock above the basal vitrophyre at this locality is extensively flow layered, and all vitroclastic textures have been destroyed. In the Pickett Creek drainage in sec. 16, T. 5 S., R. 2 W. (Figure 1), rhyolite in about the middle of the rhyolite sequence consists of brown, thin-bedded, welded air-fall tuff (agglutinate) about 15 meters thick, overlain by flow-layered and laminated, partly devitrified rhyolite that looks like typical lava. A thin section of the basal part of the "typical lava," however, shows a matrix of strung-out, highly deformed shards. The Pickett Creek locality is inferred to be close to a vent because of the occurrence of the extremely hot air fall. The vent first gave rise to airborne ash that retained sufficient heat to weld when it settled on the ground. It then gave rise to avalanching ash flows that retained sufficient heat not only to weld but also to coalesce to liquid before final emplacement and cooling.

At Sinker Creek, near an old abandoned homestead in sec. 15, T. 4 S., R. 2 W., rhyolite is exposed that is correlative mineralogically with the sequence at Pickett Creek. The rhyolite at the old homestead, however, rests directly on granite. Despite this rhyolite being flow layered and contorted, strung-out shards are preserved in some laminae within the interior of the unit (Figure 3).

ROCKS OF THE JUNIPER MOUNTAIN VOLCANIC CENTER

Juniper Mountain is a gentle structural dome about 30 kilometers in diameter that rises as a low eminence above a broad northeast-plunging depression that extends from at least 70 kilometers west of the mapped area in Oregon to the Snake River Plain about 70 kilometers east of the mapped area. The depression is virtually filled with rocks of the Juniper Mountain center and the Little Jacks center (Figure 4). The structural depression, in turn, lies within a linear, east-northeast-trending rifted region that includes the eastern Snake River Plain (Ekren and others, in press; Mabey and others, 1978; Bonnichsen and others, 1975; Christiansen and Lipman, 1972). We believe that the structural low is due to both crustal rifting along the eastern Snake River Plain trend and to magma withdrawal during the massive eruptions at the two centers.

At least five rhyolite tuff sheets were erupted within a brief interval from a buried vent complex centered near Juniper Mountain. From oldest to youngest the rocks are the tuff of Mill Creek, the tuff of Swisher Mountain, the tuff of lower lobes, the tuff...
of upper lobes, and the tuff of The Badlands. The Juniper Mountain volcanic center is not bounded by arcuate faults indicative of cauldron collapse. We believe that the lack of cauldron collapse can best be explained by an eruption from a magma chamber located at unusually great depth, perhaps 15 kilometers or more below the surface.

Tuff of Mill Creek

The tuff of Mill Creek is the least understood of the units of the Juniper Mountain center because most canyons in the area have not been cut to sufficient depth to expose this unit. The tuff is exposed only in the canyons of Boulder Creek and its tributaries east and northeast of South Mountain (Ekren and others, 1981), but it may also be exposed in the Owyhee River canyon in Oregon (Figure 4), where two collected samples are modally similar either to the tuff of Mill Creek or to the basal part of the tuff of Swisher Mountain (Figure 4, locality 638). The two units can be distinguished from each other with certainty only by their magnetic polarity, which was not determined in the Owyhee River outcrops or in any other exposure in Oregon.

The tuff of Mill Creek is over 30 meters thick, reddish gray or brown, and flow layered from base to top. The basal vitrophyre in the Mill Creek area, a tributary of Boulder Creek, is conspicuously columnar-jointed at the base. Owing to highly irregular paleotopography, the columns dip at diverse angles, commonly horizontal, and in places they display nearly vertical internal flow banding. At several localities, flattened pumice fragments are visible in the basal vitrophyre (Ekren and others, in press).

The tuff of Mill Creek has smaller phenocrysts, contains less alkali feldspar, and has reversed magnetic polarity in comparison with the tuff of Swisher Mountain.

Figure 3. Photomicrograph of preserved shards in rhyolite at Sinker Creek on the eastern flank of the Silver City Range.
Figure 4. Map showing inferred distribution of tuffs of the Juniper Mountain volcanic center and the tuff of Little Jacks Creek within Owyhee County, Idaho, west of 116° west longitude. For explanation of letter symbols see Figure 1.
Tuff of Swisher Mountain

The tuff of Swisher Mountain is as much as 200 meters thick in the vicinity of Juniper Mountain. It is reddish gray, brown, and brick red and in most localities is flow layered from base to top. In several places it displays well-developed flow breccia at its base. In exposures west of De Lamar (Figure 4), at the extreme north end of Swisher Mountain, it consists entirely of flow breccia. Farther south, however, the unit, although flow layered, is not brecciated everywhere, and flattened pumice fragments are preserved locally in the basal vitrophyre and elsewhere in the unit. Where pyroclastic textures are obscure or have been destroyed in the tuff of Swisher Mountain, thin sections show the development of tiny feldspar microlites that we regard as proof that the ash flow achieved a liquid state (Figure 5) before final emplacement. In several localities the microlites show a more pronounced flow alignment than is apparent in this figure. That the microlites formed after the ash avalanched from the eruption column rather than before is indicated by various thin sections that show incipient microlites in stretched pumice lumps but not in the enclosing matrix. We believe that the occurrence of microlites in the lumps and not in the matrix of these particular rocks is due to the presence of more volatiles trapped in the pumice. Furthermore, had the microlites formed in the magma chamber prior to eruption many undoubtedly would have been smashed during the explosive eruption process. Microlites of various sizes and shapes should have ensued. This does not seem to be the case. In most rocks containing microlites, the tiny crystals are strikingly similar in size and shape; in some rocks they are all virtually crystallites.

On Swisher Mountain, the tuff is generally less than 50 meters thick and appears to be a densely welded simple cooling unit with a vitrophyre at the base and one at the top. Southward toward Juniper Mountain, the unit thickens and shows several partial or complete cooling breaks that are marked by black vitrophyres, most of which show flattened pumice fragments. Some of the black vitrophyres are flow brecciated. Nevertheless, without evidence of erosion beneath the vitrophyres or the presence of bedded tuffs at these lithologic breaks, it is impossible to be certain whether the cooling breaks were complete. Westward in Oregon, if correlations made during a raft trip are correct (Ekren and others, in press), two or more separate cooling units are present in the tuff of Swisher Mountain in the Owyhee River canyon. The phenocryst mineralogy elsewhere in Oregon—for example, at traverse localities 271 through 274 and at locality 883 (Figure 4)—can be matched precisely with various thin sections from Swisher Mountain and from localities east and south of South Mountain (Figure 4). A sample collected and analyzed by Dalrymple and others (reported in Laursen and Hammond, 1978) and recalculated using constants of Table 2 yielded a potassium-argon sanidine age of 13.9 ± 0.28 million years (Figure 4, sample locality W-18). This is virtually the same age as the average of two dates for samples collected by Neill (1975) at Poison Creek (Ekren and others, 1981) where the tuff of Swisher Mountain is directly overlain by the tuff of Little Jacks Creek.

As mentioned earlier, the basal part of the tuff of Swisher Mountain is not easily distinguished from the tuff of Mill Creek—both are for the most part plagioclase-pyroxene rhyolites (Figure 2). However, the tuff of Swisher Mountain upward from the base shows increasing amounts of alkali feldspar, and in places toward the top it contains nearly as much alkali feldspar as plagioclase. Quartz occurs sporadically throughout the unit; most samples from widely scattered localities contain none. In general, quartz is most apt to be found in the upper one-third of the unit; locally, in the top vitrophyre, it may make up as much as 3 percent of the total phenocrysts, which
constitute about 17 percent of the volume of the rock. The pyroxene in the tuff of Swisher Mountain is principally intermediate pigeonite (C. Knowles, written communication, 1980), but a few grains of hypersthene and a few grains of clinopyroxene with a large 2V are generally present per thin section. The upper vitrophyre commonly displays abundant pumice in outcrop (Figure 6), and a thin section of this rock shows a matrix of shards.

The tuff of Swisher Mountain is magnetically normal on Swisher Mountain and in several localities near Juniper Mountain; however, we never methodically measured it from base to top in areas of maximum thickness.

The tuff of Juniper Mountain and surrounding benches are formed by two rhyolite cooling units that on high-altitude, infrared photographs and Landsat images have the appearance of two congealed masses of viscous molasses (Figure 7). Flowage of both units resulted in the formation of concentrically ridged flow lobes; as a consequence, the two units are informally called the tuff of lower lobes and the tuff of upper lobes of Juniper Mountain. A startling feature of both units is that without the lobate appearance of the units and the well-defined flowage structures visible on aerial photographs, an experienced volcanologist would not hesitate to call both units ash-flow tuffs on the basis of sparse occurrences of well-flattened pumice fragments within and at the bases of both units. We infer that both are ash-flow tuffs which coalesced in large part to viscous liquids.

Tuff of Upper Lobes

The tuff of upper lobes forms the crest of Juniper Mountain and a series of high benches more or less radially arranged around its summit (Figures 1 and 4). Unlike the tuff of lower lobes, the tuff of upper lobes does not have a brecciated basal vitrophyre. Instead, the basal part locally consists of alternating, partially welded and moderately welded tuff that grades upward into densely welded tuff and thence upward into flow-layered tuff in which nearly all pyroclastic textures have been destroyed. Exposures of partially welded tuff at the base are confined to the eastern and southeastern flanks of Juniper Mountain. The partially welded tuff apparently thins northward and westward and possibly pinches out entirely in those directions. In the northern and western exposures, the contact between the upper lobes and lower lobes is everywhere covered by thick talus, or it is hidden by the overlapping tuff of The Badlands (Figure 1). In several places along the north flank, however, the covered interval is so thin that any hidden, intervening, partially welded, nonflow-layered tuff in the vicinity of the lower lobes-upper lobes contact would necessarily be thin or absent.

On the east flank, the partially welded tuff is at least 100 meters thick and consists of alternating weakly welded and moderately welded pink, red, and reddish brown tuff that contains abundant, conspicuous pumice lapilli generally darker than the enclosing matrix. We infer that this interval includes a number of ash flows emplaced with sufficient time lapses between eruptions to cause compound cooling. At a few localities in the Beaver Creek drainage in T. 12 S., R. 4 W., the partially welded tuff can be seen to grade upward into densely welded tuff in which the pumice clasts are lighter colored than the matrix, and these show increasing degrees of flattening upward until, in a vertical distance of about 10 meters, they
become so stretched as to be nearly unrecognizable as pumice (Figure 8). Above this zone, the rock becomes flow-layered and contorted, and stretched pumice fragments are preserved only locally. The flow-layered rocks form the lobate masses so conspicuous on aerial photographs.

The outcrops show that the welded tuff did not simply become flow layered at the top because of laminar flowage (Walker and Swanson, 1968); the flow lobes reveal that the extremely hot particles in the ash flow or flows coalesced to form a viscous liquid. The difference between the tuff of lower lobes and the tuff of upper lobes is merely that the initial ash flows of the upper tuff were colder.

The gradational nature of the contact between unequivocal welded tuff and the flow-layered rock which gave rise to flow lobes precludes the possibility that the rock is hybrid, formed in part from ash flows and in part from liquid lava. Had the vent switched from spewing ash to liquid, there would necessarily have been a time lapse between the rapidly emplaced ash flows and the slowly emplaced viscous flows, and some disruption of the underlying ash would surely have occurred; none is evident. In all likelihood, the slow-moving viscous lava would have formed a flow breccia, and none is evident. We infer, instead, that the evidence of denser welding upwards in the tuff of upper lobes is due to gradually increasing emplacement temperatures as eruptions proceeded, and that the last flows were emplaced at such high temperatures that the extremely hot ash coalesced to form a liquid. The relatively restricted areas of distribution of both the lobate tuffs (about 56 kilometers in diameter for the lower lobes) suggest that their eruption columns were not nearly as high as the columns which gave rise to the widespread tuffs of Swisher Mountain and Little Jacks Creek (see later pages). The smaller columns may have been somewhat analogous to fire fountains—a possibility that was first suggested by R. L. Christiansen (oral communication, 1977).

The tuff of upper lobes typically contains 7-10
percent phenocrysts in the lower partially-welded basal part and as much as 26 percent in the upper flow-layered part (Figure 2). Except for a few sparse and poorly exposed layers at and near the top of Juniper Mountain that contain phenocrysts as large as those in the tuff of The Badlands, the relative proportions and sizes of phenocrysts remain virtually the same from base to top.

The tuff of upper lobes has normal magnetic polarity and is 13.9 ± 0.5 million years old based on potassium-argon analyses of sanidine from outcrops on the northeast flank of Juniper Mountain (Table 2).

Tuff of The Badlands

Tuff of The Badlands is the name that we informally apply to the youngest cooling unit of the Juniper Mountain volcanic center. It forms the rugged topography at The Badlands (Figure 1) where its flow-brecciated, black basal vitrophyre rests directly on red welded tuff of the upper lobes. The tuff of The Badlands was distributed over a broader area than the tuff of upper lobes. On the southern and western flanks, the tuff of The Badlands rests directly on the tuff of lower lobes, and at Poison Creek, at the extreme northeastern edge of its distribution pattern, it rests directly on the tuff of Swisher Mountain (Figure 1, T. 8 S., R. 1 E.).

The tuff of The Badlands shows more extreme mineralogic variations internally than the other units of the Juniper Mountain center display among one another. The lower part, as much as 200 meters thick, is reddish gray and weathers brown. It locally contains the largest phenocrysts found in any of the Juniper Mountain rocks. The upper part, also as much as 200 meters thick, contains perhaps the smallest phenocrysts. The unit bridges the lithologies of the tuffs of lower and upper lobes: The lower part of the tuff of The Badlands is a virtual repeat of the tuff of lower lobes, and the upper part is a repeat of the tuff of upper lobes.

In exposures on The Badlands and in the Owyhee River canyon, except for the large mass of rock exposed between Deep Creek and Battle Creek (Figure 1), the tuff of The Badlands consists only of the large-phenocryst lower part. In places in the canyon south of Lambert Table, the large-phenocryst rock is vitrophyric at the base and also at the top. The presence of the vitrophyre at the top, which is directly overlain by sedimentary rocks associated with the Banbury Basalt, show that the lower, large-phenocryst part of the tuff of The Badlands and the upper, small-phenocryst part are not a continuous simple cooling unit. Instead, the two parts are at least separated by a partial cooling break, and in the canyon exposures south of Lambert Table the upper part either was removed by erosion prior to the deposition of Banbury Basalt and related sedimentary rocks or was never deposited there.

In several exposures the tuff of The Badlands contains quartz phenocrysts as large as 8 millimeters and alkali feldspar and plagioclase phenocrysts as large as 1 centimeter. If these large phenocrysts were consistently present laterally and vertically throughout the unit, they would provide a useful criterion to distinguish the unit from the tuff of lower lobes; unfortunately they are not. Where the large grains are present, however, they are spectacular because they are so extensively resorbed. Commonly, they are completely riddled with holes and show as virtual sieves in thin section. The degree of resorption of the crystals, however, is nearly matched by resorption of the crystals in the tuff of lower lobes.

Between Deep Creek and Battle Creek, the large outcrop labeled “Tjub” (Figure 1) consists entirely of the upper lithology of the tuff of The Badlands. The contact with the lower lithology, the large phenocryst tuff, is not exposed. The exposed rock is pink, flow layered, and characterized by intense vapor-phase crystallization, but nevertheless it shows stretched pumice fragments in nearly all exposures. The rock in these exposures is as thick as 200 meters.

Elsewhere, the tuff of The Badlands is typically flow layered from base to top, and the basal vitrophyre commonly is extensively flow brecciated. In most exposures, the lower as well as the upper part
displays unequivocal stretched pumice, and thin sections from widely scattered localities display highly deformed shards. If the correlation of the unit (Figure 4) as far east as the Duck Valley Indian Reservation and to the west as far as Tent Creek in Oregon is correct, the unit is second only to the tuff of Swisher Mountain in the areal extent of units erupted from the Juniper Mountain center.

Both parts of the tuff of The Badlands are magnetically normal. Armstrong and others (1980) reported a potassium-argon date of 12.0 ± 0.2 million years on sanidine from an outcrop sampled by Neill (1975) at Poison Creek (Figure 1).

TUFF OF WILSON CREEK

The tuff of Wilson Creek occurs as a tabular sheet, much broken by minor faults, along the Snake River Plain margin and as a paleocanyon-filling tongue extending parallel to Wilson Creek. It is a simple cooling unit that locally reaches a thickness of more than 170 meters. Toward the northwest, it overlies the Jump Creek Rhyolite and toward the southeast it underlies the rhyolite tuff of Browns Creek (Figure 1). For descriptions of these units see Ekren and others (1981). The tuff of Wilson Creek must be about 11 million years old because potassium-argon ages established for both the underlying and overlying units are approximately 11 million years. The unit has reversed magnetic polarity.

The tuff of Wilson Creek is a grayish red to grayish red-purple, crystal-poor, devitrified rhyolite containing fewer than 5 percent crystals, smaller than 2 millimeters in size, of quartz and sanidine in subequal amounts, together with rare clinopyroxene. The sparse vitrophyric rocks in this unit contain a few crystals of xenocrystic(?), biotite and plagioclase. Lithic inclusions sparsely scattered throughout the unit are mostly plagioclase-rich andesites that occur in the surrounding area and, locally, directly beneath the tuff of Wilson Creek. Most outcrops of the tuff of Wilson Creek are devitrified, lithophysal, and finely flow layered. In places near the Snake River Plain margin, the flow layering is thrown into broad folds. Toward the southwest the folding disappears, and at the southwesternmost end of the paleocanyon fill, flow layering is mostly horizontal except where it steepens to meet the lateral margins of the paleocanyon.

The only known exposures of vitrophyre in the tuff of Wilson Creek are along the paleocanyon margins at the southwestern end of the canyon fill. Some of this glassy material is as flow layered as the devitrified rock. However, exposures at Wilson Bluff, at the southwestern extremity of the paleocanyon fill, show abundant collapsed pumice fragments, as large as 2 by 6 centimeters, and similar-size lithic inclusions in a shard matrix in the marginal vitrophyre. Continuous exposures allow the vitrophyre to be traced upward and channelward into patchily devitrified rock, which locally preserves pumice outlines, and then into steeply flow-layered lithophysal rock in which all traces of pyroclastic character have been erased. Continuing away from the margin, the steep flow layering flattens and merges with the layering in the inner part of the flow. No discontinuities interrupt the transition from pumice-rich vitrophyre at the paleocanyon margin to devitrified, flow-layered, lithophysal rock in the interior of the paleocanyon fill. These exposures provide firm evidence that the tuff of Wilson Creek is a welded ash flow or flows, whose fragmental texture has at most places been completely obliterated by homogenization and the formation of lithophysae. The preservation of vitroclastic texture at the paleocanyon margins appears to be due to rapid chilling.

Geologic mapping shows that the paleocanyon occupied by the tuff of Wilson Creek could not have extended much farther southwest than where it is presently filled by the southwesternmost end of the tongue-like sheet. No possible source for the unit exists to the west or south; the tuff must have been erupted from a source to the northeast now buried beneath the Snake River Plain. Detailed study in the highlands to the southwest (McIntyre, 1972) shows that streams draining the highlands flowed toward the Snake River Plain during the time when the tuff of Wilson Creek was emplaced. Thus, the tuff of Wilson Creek must have flowed up-canyon during its emplacement, additional evidence that the unit moved as an ash flow and not as a viscous lava.

TUFF OF LITTLE JACKS CREEK

A compositionally distinctive sequence of dark, flow-layered rhyolite tuff that for the most part contains only plagioclase and ferriferous pigeonite phenocrysts (determined with microprobe by C. Knowles, written communication, 1980) is well exposed throughout a large part of the eastern Owyhee Plateau. The best exposures are in Little Jacks Creek Canyon about 35 kilometers south of Grand View, where at least four and possibly as many as six cooling units are exposed (Figures 1 and 9). This sequence is referred to in this report as the tuff of Little Jacks Creek. It corresponds to the tuff of Antelope Ridge of Bennett (1976) and the rhyolite of Owyhee Plateau of Neill (1975), who obtained potassium-argon dates of 9.6 ± 2.0 million years and 10.0 ±
Figure 9. Tuff of Little Jacks Creek, Idaho, in Little Jacks Creek canyon about 8 kilometers above mouth. Note tabular appearance of these ledge-forming, flow-layered cooling units. Four cooling units are inferred at this locality: an upper, mesa-capping unit at skyline, which is about 15 meters thick; an upper middle unit about 100 meters thick that forms two distinct ledges; a lower middle unit, also about 100 meters thick, that also forms two distinct ledges; and an incompletely exposed lower unit. The four cooling units are indistinguishable on the basis of phenocryst mineralogy (Figure 2). Soft zones between cooling units consist mostly of yellow-brown tuffaceous sandstone and reworked ash-fall tuff.

1.5 million years from plagioclase separates from outcrops in Little Jacks Creek canyon (Armstrong and others, 1980).

The various cooling units in the tuff of Little Jacks Creek, although internally flow layered and contorted, are exceptionally tabular where exposed in the deep canyons (Figure 9). The basal vitrophyres are mostly flow brecciated, but the degree of development of the basal breccia varies considerably. In places, only the lower 2 meters or so shows incipient brecciation (Figure 10); elsewhere the basal breccia may be 10 meters or more thick. The lower part above the breccia may be either massive (Figure 10) or extensively flow folded (Figure 11). The devitrified rhyolite in the interior of the various cooling units is gray to purplish gray on fresh surfaces and dark purple or purplish gray on weathered surfaces; rarely it weathers deep red. Because of its well-developed flow layering, the tuff weathers into flagstones that, in most areas, completely cover intervening zones of soft tuff. The soft tuff zones show maximum thickness along the east border of the mapped area (Figure 1), which we infer is near the source area (see Bonnichsen, 1982a this volume).

The various cooling units in at least 95 percent of the outcrops have all the features indicative of lava flows and none of the characteristics of ash-flow tuffs. In a few outcrops, however, well-flattened pumice fragments are preserved, and thin sections show that the fragments are enclosed in shard-rich groundmass (Figure 12). Several thin sections of tuff of Little Jacks Creek show the development of tiny feldspar microlites like those in the tuff of Swisher Mountain (Figure 5). A few thin sections show a virtual felt of these tiny microlites, and many thin sections show them in pronounced flow alignment. The microlites must have formed after the flow coalesced to a dense, fluid mass but before the mass had come to rest.

The tuff of Little Jacks Creek displays a remarkably consistent mineralogy from base to top (Figure 2). The tuff contains from 3 to 15 percent phenocrysts consisting of 75-85 percent plagioclase that are 2-4 millimeters long, 10-20 percent pale brown or brown-

Figure 10. Base of Little Jacks Creek cooling unit near Big Jacks Creek, Idaho. Note the incipient development of basal breccia. Rhyolite rests on tuffaceous sandstone and reworked crystal-poor ash-fall tuff.
Figure 11. Flow fold at base of a Little Jacks Creek cooling unit at mouth of Little Jacks Creek canyon, Idaho. Fold is about 2 meters high.

Figure 12. Photomicrograph of thick-walled undeformed shards in basal glass of lower middle cooling unit (See Figure 9) of tuff of Little Jacks Creek.

ish green ferriferous pigeonite (C. Knowles, written communication, 1980) 1 millimeter and smaller; and from 2 percent to as much as 9 percent small Fe-Ti oxide crystals that are less than 1 millimeter. The plagioclase crystals include many that are considerably resorbed and a few that are poikilitic, containing very fine grains of pigeonite and Fe-Ti oxide. Several thin sections of tuff of Little Jacks Creek contain a few crystals of ferrohypersthene, and a few thin sections contain an occasional grain of clinopyroxene that has a large axial angle.

In a few localities in the eastern part of the area, for example at localities 64 and 119 (Figure 4), the uppermost rhyolite contains a few small phenocrysts of quartz per thin section or, less commonly, of both quartz and alkali feldspar. This rock resembles the tuff of Little Jacks Creek so closely in outcrop and thin section that genetic affinity to the Little Jacks Creek plagioclase tuff seems a valid assumption. We infer that the quartz-bearing unit constitutes one of the last products of the Little Jacks eruptive center and that the center lies just east of the eastern boundary of Figure 1. We base this conclusion on the fact that the tuff of Little Jacks Creek is thickest in this general region and that flow lineation trends (Figure 1) converge in this area. The source probably is centered a few kilometers northeast of localities 64 and 119 (Figure 4) in Townships 9, 10, and 11 S.; Ranges 4, 5, and 6 E. This area, when viewed from vantage points on the Snake River Plain, stands in gentle relief with the configuration of an inverted saucer or a flat-topped domical area. This area was mapped in reconnaissance by Malde and others (1963), and it is obvious from their map and from Landsat images that no caldera complex bounded by arcuate faults is present in the inferred source area.

We believe that a lack of cauldron collapse in this area, like that at Juniper Mountain, is due to eruption from depths that precluded such development.

CHEMISTRY AND PETROLOGY

Chemical analyses and CIPW norms for the rhyolitic rocks described in this report and for others described in Ekren and others (1981) are shown in Table 3. Comparing an average of twenty of these with the average of twenty-four calc-alkaline rhyolites compiled by Nockolds (1954) shows that Owyhee rocks are normal calc-alkaline eruptives. Thus, their high fluidity is not a function of abnormal chemistry. The rocks from the Juniper Mountain center and the Little Jacks center (Table 3), however, are richer in iron than Nockolds' average, and according to R. L. Smith and G. A. Izett (oral communication, 1978 and 1979), they are considerably richer in iron than are most rhyolites that have been described from the western United States. The abundance of iron in these rocks, however, was obviously not a critical factor that accounted for high fluidity because several of the equally fluid rhyolite tuffs from the Silver City Range (Table 3, column 2) have relatively low iron values—values that are less than Nockolds' average.

The rhyolites, whether erupted from the western Snake River Plain (Table 3, analyses 9, 10, and 11), the Silver City Range and vicinity (Table 3, analyses 1, 2, and 3), Juniper Mountain (Table 3, analyses 4 through 8), or the Little Jacks center (Table 3, analysis 12), are characterized by low Ca and exceedingly low Mg contents. According to Noble (1972, p. 143-144; oral communication, 1979), rhyolites with this chemistry are fairly typical of areas of bimodal
basalt-rhyolite volcanism, and the low Ca and exceedingly low Mg values represent their highly differentiated states. Whether the low values of the Owyhee rocks represent end stages of a differentiation process or whether they reflect early products of partial melting is moot.

The analyses of the rocks erupted from the Juniper Mountain center (Table 3, analyses 4 through 8) show that little differentiation took place during the time span of eruptive activity, which may have been as long as 2 million years. Even less took place in the Little Jacks Creek (Ekren and others, in press). The data show that the early eruptive products of a single eruptive cycle tend to be more mafic than later products. This is the opposite of the well-known compositional zonation of ash-flow tuffs produced during caldera-forming eruptions; in those tuffs the early erupted products are more silicic than those that follow. This has been attributed to progressive tapping, from the roof down, of a magma chamber with a zone of more silicic magma at the roof. This zonation appears to be a common characteristic of ash-flow tuffs associated with caldera-forming eruptions from magma chambers located at shallow depths (Lipman and others, 1966; Byers and others, 1976; Hildreth, 1979). Chemical variation in the Owyhee centers, the opposite of this, surely is attributable to some as yet unknown set of conditions or mechanisms.

Recent laboratory experiments by Whitney (1975) using high temperatures and pressures and low water contents provide some approximate limits to the conditions under which crystallization of the Owyhee rocks may have taken place (Ekren and others, in press). In brief, Whitney's data for a synthetic granite melt show that the crystallization sequence of plagioclase plus liquid to plagioclase plus quartz, a sequence occurring in the uppermost parts of the tuff of Little Jacks Creek, takes place only at temperatures greater than 1000°C, at very high pressure (8 Kb), and at extremely low water contents (2 weight-percent water or less). At lower pressures, but probably not much lower than 8 Kb, the field “plagioclase plus quartz plus liquid” disappears. Therefore, those rocks in the highest unit of the tuff of Little Jacks Creek that contain phenocrysts of plagioclase and quartz and that lack alkali feldspar must have crystallized under conditions similar to those defined by Whitney's experiments. A reasonable conclusion is that a pressure of 6-8 Kb probably prevailed during eruption of both the plagioclase-quartz cooling units of the tuff of Little Jacks Creek, whose crystallization conditions are closely constrained by the Whitney data, and the plagioclase-only tuff. These pressures suggest a depth of about 20-25 kilometers, which is within the lower crust in this region as defined by Hill and Pakiser (1966).

The inferred temperature is corroborated by analyses of iron-titanium oxides in the tuff of Little Jacks Creek and the tuff of Swisher Mountain. Equilibrium temperatures for these minerals in both units are 1000°C or higher (Ekren and others, in press). The very low water content and high temperature called for also are reflected in the anhydrous mineral assemblage that characterizes these rocks.

The experimental data of Whitney (1975) cannot be used to define the pressure prevalent during crystallization of the tuff of Swisher Mountain because alkali feldspar always is present and quartz is sparse. We infer that pressures were less than those in the Little Jacks Creek magma chamber in order to account for the marked differences in phenocryst assemblages between the two tuffs. The anhydrous phenocryst assemblage in the tuff of Swisher Mountain suggests low water contents comparable with the tuff of Little Jacks Creek and, by inference, with the derivation of the magma from similar, water-deficient source materials. The magma chambers at both centers were at depths so great that subsidence above the chambers accompanying magma withdrawal was expressed as gentle downwarping rather than as fault-bounded cauldron collapse.

No stable magma chamber could exist for long at the temperatures indicated for the times of eruption. Walls of the chamber would be under active attack by the magma. Where other evidence suggests the presence of a stable chamber the extremely high temperatures must have been limited to the time immediately prior to eruption; indeed, such eruptions may have been triggered by a sudden temperature rise. Repetition of phenocryst characteristics and chemical zonation of the tuff of lower lobes and tuff of upper lobes within a later, single cooling unit, the tuff of the Badlands, suggests that a stable magma chamber existed under Juniper Mountain that was capable of repeatedly supplying the same material. In units like the tuff of Swisher Mountain that contain enormous volumes of material within each cooling unit, it is difficult to imagine such volumes being available for eruption without storage in some kind of magma chamber, at least for a short time. In units that show only a narrow range of variation in phenocryst characteristics and chemistry, and moderate volume within each cooling unit, such as the tuff of Little Jacks Creek, there is no evidence that a stable magma chamber ever existed. There is a distinct possibility that rocks such as these were erupted directly from their depths of origin without detectable residence time in a magma chamber at moderate to shallow depth.

Many authors now believe that the most likely source of heat for producing rhyolite magmas in
regions of crustal extension is the injection of basaltic magma (Hildreth, 1979; Lachenbruch and Sass, 1978; Leeman, 1982 this volume; and Bonnichsen, 1982b this volume). Heat transfer from basaltic magma is also believed to be a common mechanism for triggering the eruption of rhyolitic rocks (Sparks and others, 1977). Heat transfer from basalt likely was involved in the generation and eruption of the Owyhee rocks because we can imagine no other way to raise these rhyolitic magmas to the eruption temperatures typical of basalt. Why this process should have operated in such a unique way in the Owyhee region remains a puzzle.

PROBABLE ORIGIN

The first comprehensive descriptions of the zones and geologic relations of welded ash-flow tuffs (Smith, 1960; Ross and Smith, 1961) showed that these rocks, in general, have features and properties that are so unlike those of typical lava flows that little room seemed to exist for possible confusion in distinguishing the two rock types. Later studies showed that many welded tuffs, in fact, exhibit features that are borderline with lavas (Hoover, 1964; Walker and Swanson, 1968; Anderson, 1970; Ekren and others, 1974). These borderline rocks, nevertheless, all have one feature in common: Their basal parts show unmistakable, flattened pumice fragments, and thin sections from various parts of the cooling units commonly show shard matrices, although most shards are so strung out as to be nearly unrecognizable. Our studies show that the Owyhee rocks are a step still farther removed from typical welded tuffs because they only locally display preserved flattened pumice fragments and shards even in their lowest parts and, to further confound matters, they commonly display flow-brecciated basal vitrophyres.

Our studies show that the southwestern Idaho tuffs were erupted at extremely high temperatures—1090°C and higher according to iron-titanium oxide compositions. At these extreme temperatures, particles within the interiors of the eruption columns and the avalanches that gave rise to the ash flows may have more closely resembled liquid droplets than rigid, angular glass shards. Perhaps, the only rigid shards and pumice fragments that existed were at the cooler tops, bases, and sides of each ash flow. These may be what we see locally preserved at the margins of and, in some tuffs, within a cooling unit containing several ash flows. We infer that in the final stages of ash-flow movement the various particles, whether rigid, semi-rigid, or liquid, coalesced in the main body of the sheet to form a nearly homogeneous viscous liquid. This liquid, then, moved sufficiently far to develop extensive flow layering and flow folds. The distance involved need not have been large—perhaps, no farther than a few hundred meters. Much of the flowage could well have been internal and could have resulted from final adjustments of the liquid to underlying topography. At this stage there may have been very little advancement of the molten sheet. The movement that occurred was completely analogous to flowage of a rhyolite lava flow.

Is it misleading or inappropriate to call the Owyhee rocks "ash-flow tuffs" when a possibility exists that most of the particles in the flows were not glass fragments but liquid droplets instead? We think not, because of the small differences in physical properties of white-hot shards and liquid droplets and because the resulting sheetlike deposits, extending 50 kilometers or more from their sources, certainly must have been emplaced in much the same way as ordinary ash flows.

REFERENCES


Ross, C. S. and R. L. Smith, 1961, Ash-flow tuffs; their origin, geologic relations, and identification:


